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CRITICAL ASSESSMENT OF THORIUM REACTOR TECHNOLOGY

By

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CRITICAL ASSESSMENT OF THORIUM REACTOR TECHNOLOGY

By

Robert A. Drenkhahn

Submitted to the Department of Nuclear Science and Engineering on May 11, 2012
In Partial Fullfillment of the Requirements for the Degree of
Bachelor of Science in Nuclear Science and Engineering

Abstract

Thorium-based fuels for nuclear reactors are being considered for use with current and future designs in both large and small-scale energy production. Thorium-232 is as abundant on Earth as lead, far more common than all isotopes of uranium, leading to its greatly reduced cost. Thorium itself offers a significantly greater neutron absorption cross-section than uranium at thermal energies, resulting in greater efficiency and smaller geometries. Certain thorium-based fuels can also significantly reduce proliferation by denaturing the thorium fuel cycle product U-233 (which is cause for proliferation concern) with U-236 and U-238. Several countries, including the USA, China, and India, are developing new conceptual designs which focus on the advantages offered by thorium. Thorium reactor technology today, as well as its practicality in the near-future, was surveyed to determine its potential for a major role in the nuclear power industry. Factors considered were economics, efficiency, waste, and proliferation. It is recommended that thorium-based fuels be further integrated in future reactor designs to take advantage of its numerous benefits in these areas.

Thesis Supervisor: Dennis Whyte

Title: Professor

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CHAPTER 1: Introduction

The race for practical Generation IV reactor designs continues; one such technology that shows potential is a thorium-fueled reactor. Though uranium-fueled reactors have dominated the industry, economic and political pressures have opened up the possibility that thorium-fueled reactor designs could compete in today's energy market. Though thorium has been demonstrated successfully in reactors as early as the 1960's, uranium came to dominate the industry as a result of the need for breeding isotopes for military use (i.e. thermonuclear weapons), as well as developing nuclear technology quickly in the face of the Cold War [1]. However, major disadvantages are present in the current designs which use uranium fuels. For instance, heat and radiation damage to the fuel assemblies requires high turnover of fuel rods and, as a result, only about 5% of the energy contained in the uranium is used. Additionally, the fission byproducts of the uranium fuel cycle significantly affect the efficiency of the reactor. One example of such a byproduct is the well-known fission poison xenon-135, which with a high neutron cross-section absorbs many of the neutrons that otherwise could have been used in uranium fission.

Global energy usage will continue to increase, requiring an increase in nations' ability to supply to the electrical grid. Though other forms of energy (i.e. coal, natural gas) are currently dominating the energy industry, political trends are moving towards cleaner forms of energy – those sources which produce the fewest carbon emissions and have the least impact on the environment. Fortunately, nuclear power eliminates the risk of carbon emissions in the production of electrical power, making it attractive regardless of the fuel used. Currently licensed designs have high capital costs, however, necessitating new research into lessening the financial burden associated with building new plants.

The numerous potential advantages offered by thorium reactor technologies (i.e. cost, safety, proliferation, efficiency) are being explored in several countries today. As new thorium concepts are developed that can overcome economic and regulatory hurdles, it may replace uranium as the dominate fuel in nuclear reactors. A critical assessment of thorium nuclear reactors today is needed to draw comparisons with more common uranium reactors and identify advantages provided by an industry focus on thorium-based designs. Whether these advantages merit the expedited development of thorium reactors as part of the energy portfolio of the United States and other countries is still in question. Much work is still being done to look at the implementation of thorium-based fuels in current and future reactor designs, and whether the inclusion of thorium will boost the competitiveness of nuclear power in the global energy market.

CHAPTER 2

Background

2.1 History

Thorium was discovered in 1828 by a Swedish chemist named Jons Jacob Berzelius [2]. It was confirmed to be radioactive by Marie Curie before the turn of the 20th century, although the radioactivity is very low, with a half-life of about 15 billion years. As an oxide (ThO_2), it has a higher melting point (3663K) than any other oxide. Naturally occurring thorium-232 is more than three times more abundant than uranium in the Earth's crust (Noting that even the fissile material in natural uranium is only a small fraction (0.7%) of what is mined) [3]. In contrast, almost all of naturally occurring thorium is the desired fertile thorium-232 needed to breed fuels for power production [2].

Many reactor designs have been tested for use with thorium-based fuels. One notable example was the US Molten-Salt Reactor Experiment in the 1960's which used uranium-233 as its fissile fuel, bred from thorium [4]. This project showed some feasibility of the thorium cycle, but it was later defunded. For most of the 20th century, breeding nuclear materials for weapons was of more concern and this fuel cycle was passed over in favor of uranium. As a result, much of the nuclear power infrastructure grew out of the bureaucratic decision to pursue uranium fuels [2].

Today, much of the focus on improving nuclear technology is reducing cost to compete with fossil fuels, increasing proliferation resistance, and ensuring safety. These factors make it necessary to take a second look at thorium as a nuclear fuel-cycle option. If research into modern designs can show thorium to have a superior advantage to uranium-based fuels, it may merit a shift in the nuclear power infrastructure of the United States, as well as other countries around the world.

2.2 The Thorium Fuel Cycle

Thorium is fertile, meaning that on the addition of a neutron source it transmutes to uranium-233 before it becomes fissile [3]. A description of the thorium fuel cycle is shown in Figure 1.

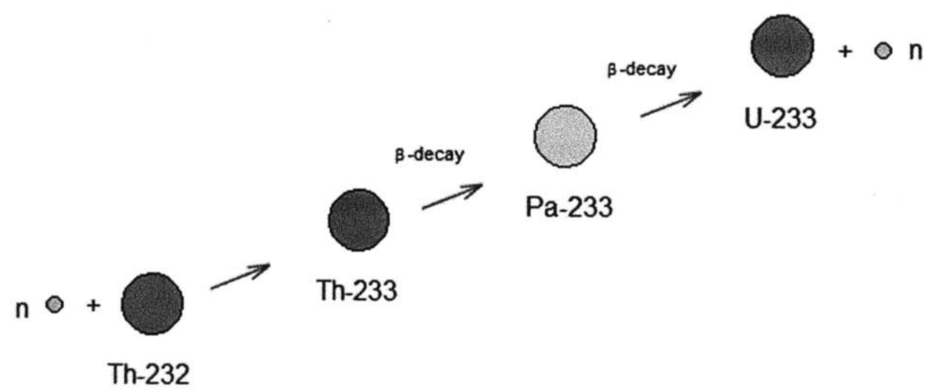

Figure 1 – Thorium Fuel Cycle (coloration is arbitrary). A source neutron transmutes Th-232 which, after a series of beta-decays, produces U-233. This isotope fissions when induced by thermal neutrons, producing more neutrons (2-2.5) to continue the cycle

Upon the addition of a neutron (meaning a neutron source is require), thorium-232 becomes unstable thorium-233 which quickly beta decays to protactinium-233. After about another month, this beta decays once more to become the uranium-233 fissile fuel, producing neutrons upon fission to continue the cycle. Operating this fuel cycle in the thermal neutron spectrum allows for improved safety and control over the uranium-238 reactors operating in the fast spectrum. The fission product wastes produced are created to a lesser extent than a uranium-fueled counterpart. The uranium-233 has a small probability, upon absorption of a neutron, to become uranium-244 [3]. This isotope can again absorb a neutron to become the fissile isotope uranium-255, which either fissions as fuel or produces progressively higher isotopes, including fissile plutonium-239. Of waste concern, however, is the Protactinium-231 (half-life of 32,760 years), which is created in a (n,2n) reaction with thorium-232 which decays to form the isotope in question, contributing much of the long-term radiotoxicity of the spent fuel.

2.2 Cost and Abundance

Thorium offers a significant cost advantage over uranium-based fuels, boosted especially by its abundance. Also, due to the inevitable decline of the relatively little fissile uranium available (which makes up 0.7% of natural uranium), the cost of uranium fuel for reactors will begin to increase as supply runs short. Fertile thorium will remain plentiful for a much longer period of time, ensuring that there will be no 'peak thorium' as there is potentially with oil and uranium. It already is mined from Monazite sands, although in this process it is currently considered a byproduct [5]. As a comparison, uranium costs about $121 per kilogram, while thorium is much cheaper. Although it does not have an official commercial quote, it is estimated to be around $33 per kilogram should it be mined for commercial use. It is currently in such low demand that a few thousand tons of thorium nitrate were simply buried in the Nevada desert. An estimation of the thorium reserves of a few select countries is listed in Table 1.

Country	Reserve Base (tons)
Australia	340,000
India	300,000
USA	**300,000**
Norway	180,000
Canada	100,000
South Africa	39,000
Brazil	18,000
Other Countries	100,000
World Total	*1,400,000*

Table 1 – Estimated thorium reserves for select countries [6]

The entire energy need of the United States can possibly be satisfied by as little as 400 tons of thorium per year [6]. This would mean that the domestic supply of thorium in the United States could last for hundreds if not over a thousand years. This is also assuming thorium being used for all of the country's energy needs; however it would be more accurate to assume a mixed portfolio of energy sources to make up the country's total power demand.

Thorium also offers higher neutron absorption cross-sections at thermal energies [3]. This allows for more efficient fuel-burning and smaller geometries which lead to lower overall design costs. A comparison of the neutron cross sections for thorium-232 and uranium-238 are given in Figure 2.

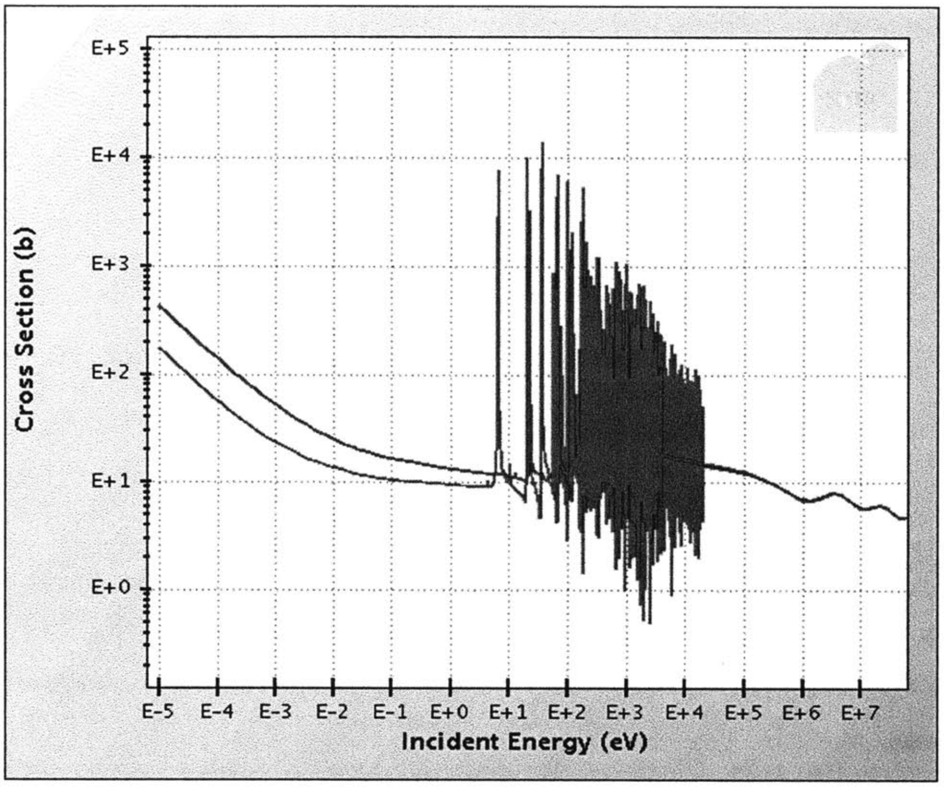

Figure 2 – Comparison of the neutron cross sections for thorium-232 (red) and uranium-238 (green). Obtained using the National Nuclear Data Center Database [7]

There is a visible difference in the thermal neutron spectrum for these two cross-sections that can be taken advantage of in core designs. With a higher absorption cross-section, the chance of a neutron escaping the core, and thus becoming unusable, decreases. This reduces the need for sophisticated reflectors or large geometries to account for neutron leakage.

Upon absorption, the thorium becomes uranium-233, a fissile isotope ideal for nuclear power generation. In comparison to uranium reactors which utilize uranium-235 and plutonium-239 as their fissile fuels, uranium-233 produces a significantly higher yield of neutrons from fission than U-235, and to a slightly lesser extent, Pu-239. A plot of the neutron yields for these three isotopes is shown in Figure 3.

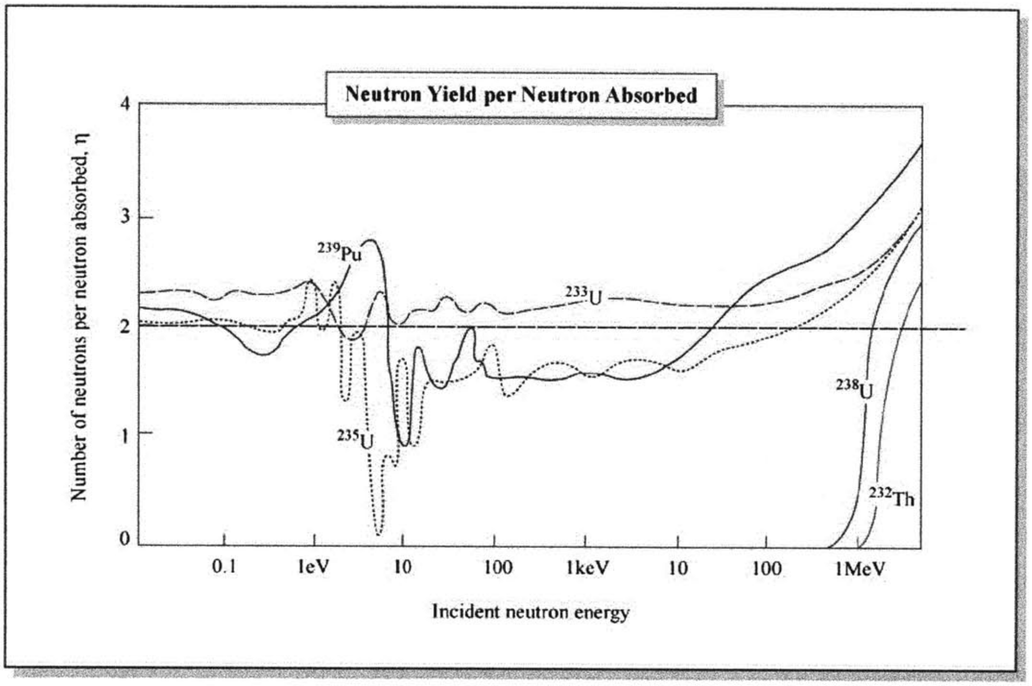

Figure 3 – Neutron Yield for uranium-233, uranium-235, and plutonium-239 [8]

This property reveals a very practical use for the thorium fuel cycle. With a thermal spectrum neutron cross-section much higher than 2, the thorium reactor becomes capable of being a breeding reactor. This means that it creates more fissile material than it consumes, and becomes highly efficient at using all of the nuclear fuel contained within [9]. By comparison, once-through Light Water Reactors (LWRs) use about 1% of the energy contained in their fuel. This is not only increases efficiency, but lessens waste and prevents the fuel cost from increasing over significant amounts of time.

Some analysis of a heterogeneous design using thorium and uranium (i.e. in a seed and blanket arrangement) suggests cost savings over the traditional PWR using UO_2 [10]. This seed (uranium) and blanket (thorium) design was explored by Radkowsky and exploited the uranium seed to provide neutrons to the thorium, allowing the breeding of uranium-233 fuel. A fuel-cycle cost analysis showed that the Radkowsky design was 4% lower than a traditional PWR, though many uncertainties could affect this outcome, along with economic changes such as material cost, mining cost, etc.

Overcoming the cost hurdle is imperative in competing with fossil fuels which currently have the advantage in upfront capital costs of producing a viable plant. If thorium-based fuels can lower not only fuel costs, but the capital cost as well (i.e. through not requiring large facilities, pressurizers and other expensive add-ons in some cases, etc.), it can be a very attractive candidate to produce a large portion of the world's power.

2.3 Proliferation Concerns

Another concern, which is more significant today, is nuclear proliferation. Uranium reactors produce waste products which can be used as the material in nuclear weapons, causing serious security concerns. Pressurized Water Reactors (PWRs) fueled with enriched U-235 produce a majority of the world's nuclear power [11]. As a result, significant amounts of plutonium are produced, as well as smaller amounts of neptunium, americium, and curium. Some thorium reactor technologies can burn these by-products along with the thorium to alleviate this risk [12]. The thorium-232 fuel cycle reduces waste production when used with a thermal neutron spectrum. In cases where uranium-233 produced by the fertile thorium is a weapons risk, denaturing the thorium fuel has been proposed to alleviate the risk of conversion to weapons-usable material. The Radkowsky design mentioned above demonstrated a significant reduction (about 80%) in the amount of plutonium remaining in the spent fuel [10]. Also, the plutonium present had a larger amount of those isotopes not useful in nuclear weapons production – spontaneous fission of plutonium-240 and plutonium-242 lessen the explosive yield of a potential bomb. Uranium-232 produced from the thorium creates gamma radiation which also makes handling the material for the purpose of a weapon difficult.

2.4 Safety Advantages

Thorium reactors have an added boost to safety because of their higher melting point and fuel thermal conductivity (In the case of thorium oxide, 5.1 W/mK at 773K and 3.0 W/mK at 1273K) [13]. These characteristics allow for a greater upper threshold for output temperatures, especially important in an accident scenario. The increase in thermal conductivity allows the thorium core to shed heat more readily to the coolant. Also relevant in certain thorium designs which utilize a liquid fuel is the added safety from not requiring a high pressure environment as is the case in PWRs [1]. Liquid-fuel reactors also provide the option of adding a freeze plug at the bottom of the reactor vessel in the event of a runaway temperature scenario, which can dispel the liquid fuel into a subcritical geometry.

2.5 Potential Disadvantages

Use of thorium-232 fuels as well as those that are thorium-232 and uranium-233 mixes can result in the creation of small amounts of uranium-232 [3]. Many of the decay products of this isotope are strong gamma emitters, causing biological concern for any workers at the reactor plant. However, this does offer an added proliferation resistance, due to the fact that it increases the danger to any person trying to acquire the materials from the spent nuclear fuel.

A major drawback in using the thorium fuel cycle is that it is merely a fertile material, thus requiring a kick start from a fissile isotope to begin the chain [13]. Such examples of an isotope include uranium-235 or plutonium-239, but one must enrich uranium-235 for practical use (which is difficult from a regulatory standpoint). Otherwise, uranium-233 must be created from pure thorium before reactor start-up, creating inefficiency at the beginning of the reactor life-cycle.

CHAPTER 3

Objectives

Though thorium-fueled reactors have already been demonstrated, the designs were not often feasible and/or failed to compete economically with uranium reactors. However, with new reactor designs using state-of-the-art materials, these challenges can be overcome in the near-future. This thesis will seek to accomplish a number of goals:

1. Gather information on the qualities of thorium-based fuels being taken advantage of today.
2. Compare these characteristics of thorium fuel with that of the traditional uranium-fuel reactors.
3. Simulate a scenario in which thorium fuel is used in a more modern design of a nuclear power plant.
4. Compare this outcome with that of the same reactor using a uranium fuel.
5. Determine what advantages a thorium-based fuel could offer
6. Offer recommendations as to whether or not thorium fuel should be more commonly implemented for future reactor designs.

The advantages most desirable are those relating to cost, efficiency, safety, and proliferation, though other factors may be considered. Though there are a plethora of reactor designs, the aim is to evaluate the potential for thorium to replace uranium in a nuclear power reactor, and the reactor design chosen will offer a particular instance where thorium can be implemented successfully.

CHAPTER 4

Methods

4.1 Identifying Potential Advantages

Literature on thorium reactor technology will be examined to gather information on various uses of thorium in commercial nuclear reactors. In addition, research into details such as cost, proliferation, safety, as well as the associated properties of uranium fuels will be needed to provide a comparison between the two options. In order to consider strong support for the use of thorium fuels in future reactor projects, a significant advantage and ease of transition is required. This information will form the qualitative portion of this assessment.

4.2 Modeling an Example in MCNP

A thorium reactor concept is modeled in the Monte Carlo N-Particle Transport Code, or MCNP [14]. The core model consists of a defined geometry and material specification, along with associated cross section data. Input files allow the user to define individual cells and surfaces, assigning material value integers to create the layout of the given design. MCNP then tracks neutron histories from creation using cross section data libraries which give those cross sections for elastic scattering, inelastic scattering, and absorption for the materials present in the design.

Simulations will confirm the plausibility of thorium fuel in this reactor setup through Monte Carlo analysis, determining a comparative k-effective value using various fuel blends. This can be compared to the original uranium-based fuel design to show any reduction of cost due to cheaper fuel (both price of the fuel and the amount required for a given geometry for a self-sustaining reaction will be taken into account). K-effective, the multiplication factor, is defined as the ratio of thermal neutrons that induce fission from one generation to the next, and can also be related to the six-factor formula shown in Equation 1.

$$k_{eff} = \epsilon \, L_f \, p \, L_t \, f \, \eta \qquad (1)$$

In this formula, k-eff represents the multiplication factor, ε is the fast fission factor, L_f is the fast spectrum non-leakage probability, *p* is the resonance escape probability, L_t is the thermal spectrum non-leakage probability, *f* is the thermal utilization factor, and η is the reproduction factor (number of fission neutrons per absorption) [15]. Providing this quantitative analysis will strengthen an eventual recommendation as to the attractiveness of a switch to thorium fuels.

4.3 The Lead-Bismuth Eutectic Cooled Reactor

A lead-bismuth eutectic cooled fast reactor was recently explored at MIT [16]. The original design calls for uranium mononitride (UN) fuel and a T91 steel clad. An example of the core's hexagonal shape is shown in Figure 4. Twelve rings of assemblies hold fuel pins, boron carbide control rods, a magnesium oxide reflector, as well as a boron carbide shield. Lead-Bismuth eutectic coolant surrounds the arrangement and flows between assemblies.

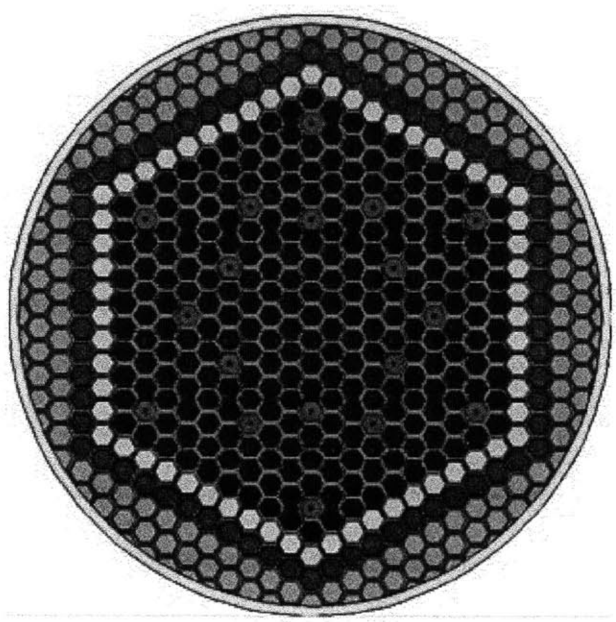

Figure 4 – An example of a Lead-Bismuth Eutectic cooled core with a hexagonal array of assemblies [16]

Uranium mononitride is a typical fuel in commercial nuclear reactors, with a high melting point and superior thermal conductivity to uranium dioxide. The fuel rods in this previous analysis were partitioned into different enrichment zones, with higher enrichment in the bottom two-thirds of each fuel rod (about 2.5% more enrichment in this zone).

4.4 The Thorium-Based Fuels

The thorium-based fuels chosen to experiment with inside the core design were an assortment of fuel mixtures. One of these was 95% thorium oxide (ThO_2) and 5% plutonium oxide (PuO_2). The plutonium is present to supply neutrons to the thorium to allow its transmutation to uranium-233 for fuel. This also allows for surplus plutonium to be used for the purpose of creating energy, instead of being stored away and at risk of theft. Thus, using the plutonium reduces the proliferation of nuclear materials that could potential be used for weapons.

A second set of fuels used varying mixtures of thorium-232 and uranium-233 oxides in three molecular densities – 50% ThO_2 and 50% $U_{233}O_2$, 90% ThO_2 and 10% $U_{233}O_2$, as well as 97% ThO_2 and 3% $U_{233}O_2$. Each fuel was simulated to determine a difference in k-effective with all other factors equal. These values were plotted to observe their relative change from the uranium mononitride results.

CHAPTER 5

Results and Discussion

5.1 Data

The results of the uranium mononitride fuel in the lead-bismuth eutectic cooled reactor are shown in Figure 5.

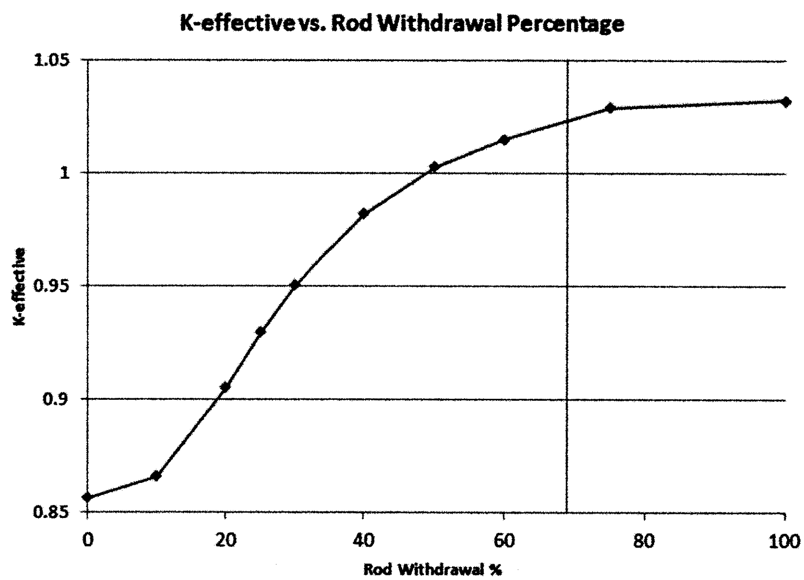

Figure 5- K-effective as a percentage of control rod insertion, with 100% being fully withdrawn [16]

The core was designed such that the control rods, when fully withdrawn, would allow for criticality and when fully inserted, would be subcritical. The red line denotes the border of the two enrichments zones in the fuel rods. Figure 6 displays a collection of the k-effective measurements for various percentages of control rod insertion for each of the thorium-based fuels (95%ThO_2-5%PuO_2, 50%ThO_2-50%$U_{233}O_2$, 90%ThO_2-10%$U_{233}O_2$, 97%ThO_2-3%$U_{233}O_2$).

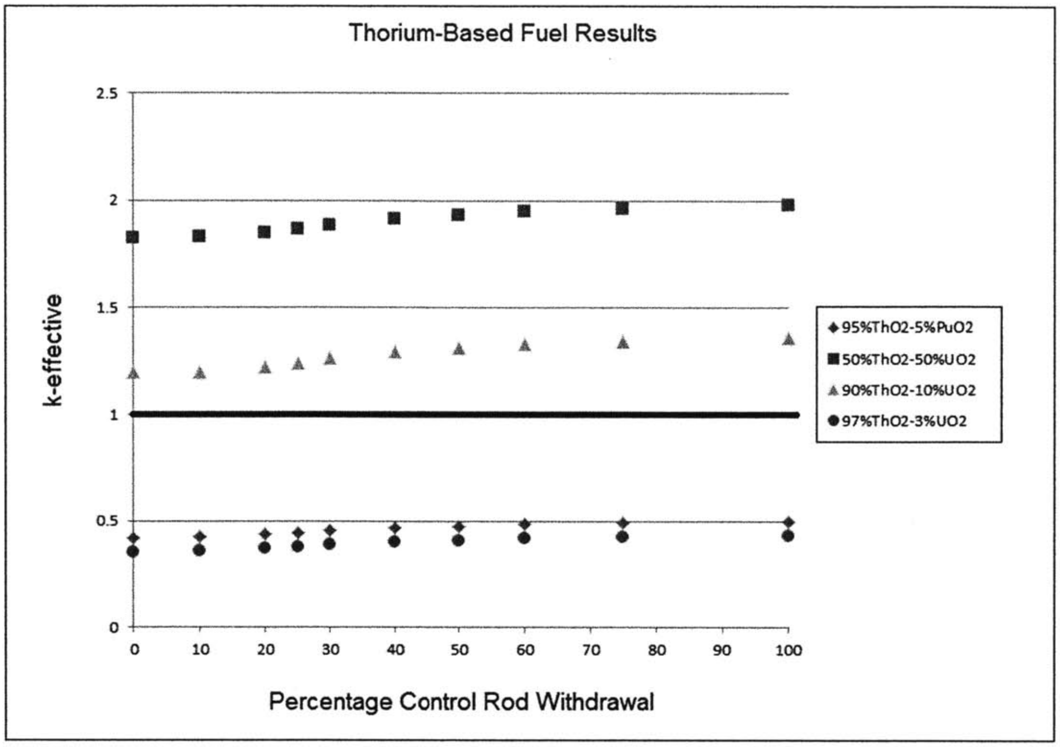

Figure 6 – K-effective measurements for the thorium fuels in the hexagonal core, keeping all else equal relative to the uranium mononitride simulation

K-effective is shown along the y-axis with a value of 1 (criticality) highlighted in bold. Measurements were taken at a range of percentages in which the fuel rods were withdrawn, including fully inserted and fully withdrawn scenarios. A list of the range of values at these percentages are presented in Table 2.

K-effective for Thorium Fuels at Various Control Rod Positions

Percent Withdrawn	95%ThO2-5%PuO2	50%ThO2-50%UO2	90%ThO2-10%UO2	97%ThO2-3%UO2
0	0.42	1.822	1.198	0.356
10	0.425	1.83	1.2	0.358
20	0.436	1.85	1.225	0.37
25	0.446	1.868	1.243	0.38
30	0.454	1.884	1.264	0.389
40	0.47	1.913	1.295	0.402
50	0.477	1.931	1.315	0.411
60	0.485	1.95	1.33	0.418
75	0.49	1.964	1.347	0.424
100	0.5	1.977	1.36	0.43

Table 2 – Various k-effective measurements for thorium fuels

The values listed feature values both of higher and lower k-effective values than the uranium mononitride data set.

5.1 Discussion

The value of k-effective determines whether there is an exponential change (growth or decay) present in the neutron population. Therefore, the range needed in a nuclear core must contain a range of values both above and below 1. Choosing various blends of thorium and uranium-233 helps to understand how much the thorium must be prepared (bred to uranium-233) in order to achieve a mix that encompasses the required k-effective value (noting that it only specifically applies for this reactor design). There are two choices when trying to approach this ideal range. First, the designer can simply find a ratio of materials in the fuel that solves the problem. The second option is to alter the design to raise or lower the contribution of the six factors in Formula 1. This is of particular interest if there is an economical mix of thorium-uranium that has a higher k-effective than the original uranium fuel, because the reactor can potentially be simplified or made smaller (increasing neutron leakage) to bring the value range of k-effective down. This can possibly create savings that offset the cost of processing the thorium to create the desired fuel (keeping in mind that natural thorium is inherently cheaper than uranium to begin with).

In the mixture of thorium and uranium-233 with the ratio or 90%-10%, the range is quite close to what one would need. Reducing the size of the core can allow for increased neutron loss to leakage and reduce the k-effective range. This would, however, reduce the amount of energy being transferred to the coolant.

Though thorium has been showed to offer advantages in proliferation resistance, a more important factor to consider is cost. To produce a fuel of these types can be expensive, and any advantages should be considered to help nuclear compete against other sources of energy. A given quote of a uranium oxide fuel was as high as 1600 dollars per kilogram [17]. This high cost is due to the amount of processing and enriching that must take place to get a usable fuel. Uranium mononitride is even more expensive to produce, so if thorium maintains its cost advantage over uranium oxides, it would be able to replace uranium mononitride to reduce costs in this instance. The cost of producing a thorium fuel with uranium-233 to begin the fuel-cycle is also quite expensive. Some studies have shown that even with the high cost of fabricating the uranium-233 fuel, the cost still falls short of enriched uranium fuels [18].

Using thorium in this lead-bismuth cooled reactor may not be the most ideal use, though, as many argue for liquid fluoride thorium fuel designs [1]. Such designs are theorized to be able to produce 1GW of power for as little as 1 million dollars (US) per year [20]. This is compared to 30 million dollars per year with a uranium plant of similar power output. These reactors also reduce capital costs (the most critical requirement in competing economically) from over a billion dollars to around 250 million dollars (This is due to a lack of shielding required and meltdown resistance offered form these molten-salt designs). Their proliferation resistance reduces security forces, and they also require less maintenance, further driving down operational costs (A comparison table of costs is presented in the appendix). It is also noted that an advantage of thorium reactors is to use a large quantity of smaller reactors to produce larger energy outputs, instead of the gigantic LWRs in use today. These reactors could take advantage of high thermal efficiency to further reduce the cost of operation, in addition to their strengths in safety and proliferation resistance. Should thorium reactor technology be developed extensively, the economic advantages are potentially tremendous.

CHAPTER 6

Conclusion

Various experiments using thorium as a nuclear fuel have been studied to find the numerous advantages that can be taken advantage of to help improve the position of the nuclear power industry. Using this fuel cycle can lead to smaller and more efficient reactors to suit energy needs. Arbitrary blends of thorium fuels with uranium-233 have been shown plausible in a lead-bismuth cooled reactor, though many numerous designs may also find advantages with this fuel. The thorium fuel option is important to continue studying, especially with the primary concerns of today being energy independence, environmental safety, and non-proliferation of nuclear materials. The energy situation has changed such that nuclear power has a unique opportunity to take a leading role in producing the world's power demand. Economic competitiveness is essential, while continuing to pursue safe and efficient designs. Thorium fuel has been found to possess many attributes that give advantages to cost, safety, efficiency, and proliferation. For these reasons, it is recommended that thorium fuels be included in future designs in order to ensure the most competitive cost for nuclear power plants in the energy market.

Future work should continue to exploit qualities of thorium fuel that drive down costs, both capital and operational. If a major advantage can be gained economically over other sources of energy (i.e. coal, oil, natural gas), nuclear power can come to dominate the energy portfolio of the United States and other nations as well.

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APPENDIX

Cost Type	Uranium LWR	Liquid Flouride Thorium Reactor (LFTR)
Capital Cost (millions/yr)	1100	250
Fueling Cost (millions/yr)	30	1
Maintenance/Staffing Cost (millions/yr)	50	5

Cost Estimates of a Uranium LWR and a LFTR [20]